Patent Application

of

Guoguang Li, Phillip Walsh and Abdul Rahim Forouhi

for

Method and Apparatus for Examining Features on Semi-Transparent and Transparent Substrates

FIELD OF THE INVENTION

The present invention relates generally to methods and apparatus for optically examining features on semi-transparent substrates and especially to examining a number of adjacent features on such semi-transparent substrates.

BACKGROUND OF THE INVENTION

In the production of miniaturized objects such as miniature devices including integrated circuits and microelectronics for semiconductor and display applications, the tools and auxiliary structures used in their manufacture, as well as the miniature objects themselves have to be examined carefully. Optical

methods of examining these tools and objects are non-destructive and frequently preferred over other approaches. Hence, advances in optical examination of miniature features including patterns composed of adjacent features are important.

In many cases miniature devices are made by photolithographic techniques. In a typical application of the photolithographic technique, a layer of photoresist is deposited on a substrate or other device layer and then exposed to radiation of appropriate wavelength through a patterning mask. Of course, the masks themselves also need to be appropriately patterned with miniature features to be able to perform their function and are thus themselves a class of miniature devices that has to be examined.

Now in photolithography certain regions of the photoresist layer are exposed and others are not, according to the pattern defined in the patterning mask. Exposing the photoresist to radiation changes its solubility. After exposure, solvent is used to remove regions of higher solubility photoresist, leaving regions of "hardened" photoresist at sites on the device layer as dictated by the patterning mask. The "hardened" photoresist remains to protect the underlying material from removal during a subsequent etching step or other suitable material removal procedure. After etching the photoresist is discarded. In this manner, a feature is created in the device based on the pattern defined in the mask.

Clearly, the photoresist layer must be accurately patterned to form features to the exacting specifications for miniature devices. It is therefore desirable to monitor the photolithographic process at various stages and on a periodic basis. For example, it would be desirable to measure the thickness of the photoresist layer and examine the pattern to determine feature sizes. The thickness can be measured by subjecting the photoresist to light with a wavelength in the range of 190 to 1000 nm and measuring the reflected light. The reflected radiation may be correlated to photoresist thickness. The general principle of this measurement technique is that the measured light reflected from a substrate is modulated by constructive and destructive optical interference from an overlaying semitransparent material such as the photoresist. For more information see Chopra, K.L., *Thin Film Phenomena*, p. 99 (McGraw Hill, 1969). The periodicity of the reflectance spectra can also be used to determine optical properties, such as the refractive index n of the substrate.

Measurement of the pattern or features is a more difficult procedure. For example, in a typical application, the pattern consists of a plurality of stripes and spaces, e.g., a line and space pattern. These types of patterns are frequently encountered in forming diffractive elements such as lenses or gratings in semiconductors or glass, forming fluid flow microchannels in silicon, and in general for providing a variety of mechanical features in a substrate. In measuring stripe widths and separations the prior art techniques have typically

relied on scanning electron microscopy (SEM). Unfortunately, SEM is a destructive and very time-consuming examination method.

Methods such as atomic force microscopy (AFM) and profilometry are also viable for examining features or patterns of features. However, both of these methods are very time consuming and they require special test structures in most cases.

The patterning masks used to create resist lines often themselves contain features. Of particular interest are Alternating Phase Shift Masks (AAPSMs), which are often quartz or fused silica plates etched with trenches in repeating patterns. This creates an interference condition between light passing through the etched and un-etched regions of the mask, leading to complete amplitude cancellation in regions that would normally have been exposed. In this way an AAPSM can be used to pattern features in the resist that are smaller than the wavelength of light used to expose the resist. Accurate metrology control of the dimensions of these features is critical, since in a typical application using 248 nm wavelength light, approximately 13 Å difference in trench depth is enough to change the phase shift by 1 degree.

In addition to AFM, SEM, and profilometry the prior art offers interferometric techniques for measuring high-precision patterns, such as those encountered in AAPSMs. Unfortunately, because of the inherent limitations of AFM, SEM and profilometry already mentioned, these techniques are not satisfactory for examining AAPSMs. Interferometric techniques are too expensive,

and require special test structures. Furthermore, the test features have to be large enough so that reference and measurement beams can be fully covered by two different uniform areas respectively. These test features often do not reflect the phase shift characteristics of the features to be printed on the mask. In addition, in most cases the test features have to be transparent. This condition prevents the measurement from being performed at the early stages of mask processing when an opaque metallic layer, such as Cr, is frequently present.

For more information on AAPSMs and methods for examining them the reader is referred to Cynthia B. Brooks, et al., "Process Monitoring of Etched Fused Silica Phase Shift Reticles", Proceedings of the SPIE, 22nd Annual BACUS Symposium on Photomask Technology and Management, September 30 - October 4, 2002, Monterey, CA, USA; Alessandro Callegari and Katherina Babich, "Optical Characterization of Attenuated Phase Shifters", SPIE, Vol. 3050, pp. 507-514; as well as Pieter Burggraaf, "Lithography's Leading Edge, Part I: Phase Shift Technology", February 1992, pp. 43-47.

More recently, attempts have been made to measure patterns using scatterometry. In this technique, a pattern is subjected to light, such as from a laser, typically having a single wavelength. This light is usually directed toward the pattern at some angle to the normal. The light reflected from the pattern at various diffracted orders is measured. It may be possible to use such data to obtain quantitative information about the pattern. However, scatterometry is very sensitive to

small changes in the profile of the pattern, and requires relatively sophisticated correlation work to relate the reflected radiation to the features of a pattern. The computational effort required to correlate the reflected radiation to the pattern is very high since the convergence criteria for these solutions take a very long time to compute. In addition, the measured pattern must be periodic. Other examples of characterization methods pertaining to photolithography and equipment suitable for practicing such methods are described in U.S. Pat. Nos. 5,867,276; 5,363,171; 5,184,021; 4,866,782 and 4,757,207. There are still other types of scatterometry, which measure the specularly reflected light as a function of wavelength, as taught in U.S. Pat. Nos. 6,483,580; 5,963,329; 5,739,909 and 5,607,800.

Of these references U.S. Pat. No. 5,607,800 to Ziger teaches a method and arrangement for characterizing features of a patterned material on an underlayer. His approach is based on selecting an appropriate wavelength range where the patterned material absorbs more radiation than the underlayer. In other words, substrate or underlayer is more reflective than the pattern or surface features in this wavelength range. The reflectance spectrum uniquely identifies the pattern and can be used to study similar patterns by comparing their reflectance spectra. Unfortunately, just as in the case of scatterometry, when patterns vary this comparison-based approach can not be used effectively to study patterns which differ substantially from each other.

U.S. Pat. No. 6,100,985 to Scheiner et al. teaches a method for measuring at least one desired parameter of a patterned structure having a plurality of features. In this method a measurement area, which is substantially larger than a surface area of the structure defined by the grid cycle, is illuminated by an incident radiation of a preset substantially wide wavelength range. The light component that is substantially specularly reflected from the measurement area is detected, and measured data representative of photometric intensities of each wavelength within the wavelength range is obtained. The measured and theoretical data are analyzed and the optical model is optimized until the theoretical data satisfies a predetermined condition. Upon detecting that the predetermined condition is satisfied at least one parameter of the structure can be calculated.

A still more recent teaching for optically determining a physical parameter of a pattern made up of features is taught in U.S. Pat. No. 6,327,035 to Li et al. This teaching goes further than Scheiner et al. by examining various response light fractions including an underlayer light fraction and a feature light fraction and using reference physical parameters of the underlayer. The response light can be either transmitted or reflected and the reference physical parameters of the underlayer are either known a priori or determined.

U.S. Pat. No. 6,340,602 to Johnson et al. teaches a method for measuring a parameter associated with a portion of a sample having one or more structures with at least two zones each

having an associated zone reflectance property. The at least two zones are illuminated with broadband light, the reflected light is measured and a measured reflectance property is fit to a model. The model mixes the zone reflectance properties to account for partially coherent light interactions between the two zones.

Although Johnson's approach attempts to address coherence issues between the zones, it does not take into account the interactions between the broadband light and the substrate. More precisely, in this approach the substrate is assumed to be opaque and only lateral incoherence between the zones themselves is treated. In most cases, however, substrates on which features or zones are measured are at least partially transparent over a portion or even the entire broadband spectrum of the incident broadband light. Thus, by leaving out the complex interactions between the illuminating light, the zones and the substrate, Johnson is not able to provide a method that can be used for measuring zones or features on semi-transparent and transparent substrates.

In fact, the problem of optically examining features and patterns on underlayers or substrates that are at least semi-transparent or fully transparent has eluded a satisfactory solution because of its complexity. This complexity is partly due to the large series of internal reflections and transmissions affecting the response light obtained from the substrate and features. What is more, the response light is not only conditioned by the multiple internal reflections and

transmissions within the substrate and features to be examined, but also by coherent and incoherent interactions between reflected and/or transmitted response light from the substrate and the various features.

OBJECTS AND ADVANTAGES

In view of the above, it is a primary object of the present invention to provide a method and apparatus that enables a thorough optical examination of features on semi-transparent and even transparent substrates. More specifically, it is an object of the present invention to provide a method of examining the response light in a manner which takes into account the coherent and incoherent interactions between reflected and/or transmitted response light within and among various features.

These and numerous other objects and advantages of the present invention will become apparent upon reading the following description.

SUMMARY

The objects and advantages of the present invention are secured by a method for determining a physical parameter of features on a substrate by illuminating the substrate with an incident light covering an incident wavelength range $\Delta\lambda$ where the substrate is at least semi-transparent and such that the incident light enters the substrate and the features. A response light received from the substrate and the features is measured to obtain a response spectrum of the response light. Further, a complex-valued response due to the features and the substrate is

computed and both the response spectrum and the complex-valued response are used in determining the physical parameter. This physical parameter can be a depth, a width, a real part of the complex refractive index, an imaginary part of the complex refractive index or some other physical parameter of the features.

The response light is reflected light, transmitted light or a combination of the two and it can be either polarized or unpolarized. Thus, the response spectrum corresponds to either a reflectance R, a transmittance T or both. The complex-valued response typically includes a complex reflectance amplitude, a complex transmittance amplitude or both. In accordance with the method of invention, when the complex-valued response is or includes the complex reflectance amplitude the reflectance R is computed by multiplying the complex reflectance amplitude with its complex conjugate. Similarly, when the complex-valued response is or includes the complex transmittance amplitude the transmittance T is computed by multiplying the complex transmittance amplitude with its complex conjugate.

A vertical coherence length L_{vc} of the incident light and thickness d_s of the substrate determine whether the response light is coherent or incoherent. For example, when the vertical coherence length L_{vc} is small with respect to thickness d_s then the response light exhibits incoherence. In such cases a phase δ_s of the complex-valued response is averaged in the computation.

The method of invention is particularly advantageous when the features are adjacent. In most such cases the wavelength range $\Delta\lambda$ is selected such that the substrate and the adjacent features produce a coherent fraction and an incoherent fraction in the response light. Preferably, further computations are made to determine a coherent fraction β (or coherent factor) for coherent adding of the complex-valued response. An incoherent fraction of the response light is equal to $1-\beta$. The coherent fraction β can be determined from a lateral coherence length L_{1c} of the incident light. It should be noted that this approach presents a closed-form solution to determining the complex-valued response of adjacent features on a substrate.

In cases where the features are periodic the incident light will experience diffraction. Thus, when the features are periodic it is preferable to focus the incident light to an illumination area covering a sufficiently small number of features such that diffraction effects are negligible.

When the area of the features is larger than the lateral coherence length L_{1c} of the incident light then the complex-valued response from the features is added incoherently. Otherwise, when the area of at least one of the features is smaller than the lateral coherence length L_{1c} then the complex-valued response is added coherently. It should be noted that lateral coherence length L_{1c} as well as vertical coherence length L_{vc} are wavelength dependent.

The features can be adjacent features made of two different materials, such as material 1 covering a first area fraction a_1 and material 2 covering a second area fraction a_2. The area fractions a_1 and a_2 correspond to the fractional area illuminated by the incident light. Depending on the embodiment, the complex-valued response to be added coherently is a total complex-valued reflectance amplitude r_C, a total complex-valued transmittance amplitude t_C or both. The following equations are used in the computations:

$$r_C = a_1 r_1 + a_2 r_2,$$

$$t_C = a_1 t_1 + a_2 t_2, \text{ and}$$

$$a_1 + a_2 = 1.$$

The response spectra such as a coherent reflectance R_C and coherent transmittance T_C are then computed by multiplying out the complex-valued amplitudes by their complex conjugates. In particular, coherent reflectance R_C is computed by using the following cross term:

$$\left\langle r_1 \cdot r_2^* \right\rangle = \frac{r_{1,as} r_{2,as}^* + \left(t_{1,as} t_{2,as}^* t_{1,sa} t_{2,sa}^* - r_{1,as} r_{2,as}^* r_{2,sa} r_{2,sa}^* \right) r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}}{1 - r_{1,sa} r_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}},$$

where α_s is an absorption coefficient of the substrate and d_s is the thickness of the substrate. In embodiments where the incident light is focused on a back side of the substrate, the cross term simplifies and is computed as:

$$\left\langle r_1 \cdot r_2^* \right\rangle = t_{1,as} t_{2,as}^* t_{1,sa} t_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}.$$

Meanwhile, coherent transmittance T_C is calculated by using the following cross term:

$$\langle t_1 \cdot t_2^* \rangle = \frac{t_{1,as} t_{2,as}^* t_{1,sb} t_{2,sb}^* e^{-\alpha_s d_s}}{1 - r_{1,sa} r_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}} = Ae^{i\phi},$$

where A is the amplitude of $\langle t_1 \cdot t_2^* \rangle$, ϕ is the phase shift between t_1 and t_2. As before, α_s is the absorption coefficient and d_s is the thickness of the substrate.

The method of invention can be practiced under various illumination conditions. In one embodiment the incident light is collimated. In another embodiment, the incident light is focused. For example, the incident light is focused on a surface of the substrate. The substrate can be illuminated from a first side where the feature or features are located or from a side opposite the first side. It should also be noted that the incident light can be linearly polarized.

In certain applications of the method the physical parameter is derived from phase shift ϕ or amplitude A of the response light. In other words, phase shift ϕ and/or variation of amplitude A experienced by reflected and/or transmitted response light is used to determine the physical parameter of the features. In some embodiments, information about physical parameters of the features is derived from phase shift ϕ. Specifically, in embodiments where the response light is transmitted the phase shift ϕ can be obtained from:

$$\phi = \phi_T = \frac{2\pi(n\cos\theta_2 - \cos\theta_1)t_s}{\lambda}.$$

In embodiments where the response light is reflected the phase shift ϕ can be obtained from:

$$\phi = \phi_R = \frac{4\pi n t_s \cos\theta_2}{\lambda}.$$

In the preferred embodiment where at least two adjacent features are being examined the incident light enters the substrate and the features and the complex-valued response exhibits interference due to the features. The interference manifests in phase ϕ observed in the measured response light. In order to examine these variations it is convenient to examine a wide reflectance R and/or transmittance T spectrum, e.g., from about 190 nm to about 1000 nm.

The method of invention can be used to determine physical parameters of features in various arrangements. For example, at least one of the features can be in the form of a film, e.g., a flat film. One or more additional features can be embedded in the film.

The invention further extends to an apparatus for determining a physical parameter of one or more features on a substrate. The apparatus has an illumination source for producing the incident light and optics for guiding the incident light such that the

incident light enters the substrate and the features. A detector is provided for receiving the response light and measuring its response spectrum. In addition, the apparatus has a processing unit for computing the complex-valued response of the substrate and the one or more features and determining the physical parameter from the measured response spectrum and the complex-valued response.

The substrate can be transparent within the incident wavelength range $\Delta\lambda$ or optically thick. In practice, the substrate will exhibit a variation in its degree of transparency over the selected wavelength range $\Delta\lambda$. In some cases, the substrate can be optically thick over a large portion of the entire wavelength range $\Delta\lambda$, e.g., when the substrate comprises a metal layer. In a preferred embodiment the apparatus examines a wide wavelength range $\Delta\lambda$ by providing an illumination source that is broadband. In one embodiment the broadband illumination source provides an incident wavelength range $\Delta\lambda$ from about 190 nm to about 1000 nm.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 (PRIOR ART) is a schematic diagram illustrating some optics principles on which the invention is based.

Fig. 2 is a diagram illustrating an apparatus according to the invention for examining a semi-transparent substrate with adjacent features.

Fig. 3 illustrates a cross-sectional view of a fused silica sample etched with adjacent features.

Fig. 4 are graphs of reflectance and transmittance spectra R, T for the sample of Fig. 3.

Fig. 5 is a graph of phase shift for the sample of Fig. 3.

Fig. 6 are graphs of transmittance T spectra for samples analogous to that of Fig. 3 and having varying area fractions of trenches.

Fig. 7 are graphs of normalized reflectance spectra from back side (**b**) for samples analogous to that of Fig. 3 and having varying area fractions of trenches.

Fig. 8 are graphs of normalized reflectance spectra from front side (**a**) for samples analogous to that of Fig. 3, normalized relative to a uniform sample, and having varying area fractions of trenches.

Fig. 9 is a cross sectional view of a portion of another fused silica sample examined with the method of the invention.

Fig. 10 is a cross sectional view of a portion of yet another fused silica sample examined with the method of the invention.

Fig. 11 are graphs of reflectance R spectra measured on the sample of Fig. 10 from the front side and the back side.

Fig. 12 (PRIOR ART) is a diagram of a standard transmission-type interferometric apparatus examining a substrate with features.

Fig. 13 is a diagram illustrating the method of invention using response light reflected from the front side of the substrate with features as shown in Fig. 12.

Fig. 14 is a diagram illustrating the method of invention using response light reflected from the back side of the substrate with features as shown in Fig. 12.

Fig. 15 is a diagram illustrating the method of invention using transmitted response light from substrate with features as shown in Fig. 12.

Fig. 16 illustrates a portion of another apparatus according to the invention.

THEORETICAL BACKGROUND

The instant invention will be best understood by first considering the prior art schematic diagram of Fig. 1 illustrating some optics principles. Apparatus **10** has an illumination source **12** that generates an incident light **14** spanning an incident wavelength range $\Delta\lambda$. Source **12** is positioned to illuminate a substrate **16** with incident light **14.** Optics **18** are positioned to guide incident light **14** from source **12** to substrate **16.**

Substrate **16** has a thickness d_s typically on the order of a fraction of a millimeter to several millimeters, e.g., 0.2 mm to 8 mm. Substrate **16** can be made of any material that is semi-transparent within an incident wavelength range $\Delta\lambda$ covered by

incident light **14**. The material of substrate **16** is optically described by a real part n_s and imaginary part k_s of the complex refractive index. For example, the material of substrate **16** can be diffused silica or glass.

Substrate **16** has a stack of films **36** on a first side **a** and a stack of films **38** on a second side **b**. Stack **36** can include a large number of films **36A, 36B, ... 36N**. Likewise, stack **38** can include a large number of films **38A, 38B, ... 38N**.

Incident light **14** enters substrate **16** through stack **36** deposited on a side **a** of substrate **16**. It should be noted that films **36** can have any structure and composition and represent features. Now, when incident light **14** enters substrate **16** from side **a** two complex-valued responses due to substrate **16** and stacks **36, 38** are produced. The first complex-valued response is a complex reflectance amplitude r and the second complex-valued response is a complex transmittance amplitude t, given by:

$$r = \frac{r_{as} + \left(t_{as}t_{sa} - r_{as}r_{sa}\right)r_{sb}e^{-i\delta_s - \alpha_s d_s}}{1 - r_{sa}r_{sb}e^{-i\delta_s - \alpha_s d_s}}, \qquad \text{Eq. 1}$$

$$t = \frac{t_{as}t_{sb}e^{-(i\delta_s + \alpha_s d_s)/2}}{1 - r_{sa}r_{sb}e^{-i\delta_s - \alpha_s d_s}}. \qquad \text{Eq. 2}$$

In these equations δ_s is the phase and α_s is the absorption coefficient given by:

$$\delta_s = \frac{4\pi n_s d_s \cos\theta_s}{\lambda}, \qquad \text{Eq. 3}$$

$$\alpha_s = \frac{4\pi k_s \cos\theta_s}{\lambda}. \qquad \text{Eq. 4}$$

In these equations "a" denotes side **a**, "b" denotes side **b**, s denotes substrate **16**, d_s is the thickness of substrate **16**, n_s, k_s are the real and imaginary parts of the complex refractive index of substrate **16** and θ_s is the incident angle of light **14** inside substrate **16**. Coefficients r_{uv} and t_{uv} (u,v = a,b,s) are the reflection and transmission coefficients. For example, t_{as} is the transmission coefficient from the atmosphere surrounding substrate **16**, in this case air, through stack **36** on side **a** to substrate **16**, and t_{sa} is the transmission coefficient from substrate **16** through stack **36** on side **a** to air. The analytical expressions for r_{uv} and t_{uv} are well known and can be found in standard textbooks, such as O.S. Heavens, *Optical Properties of Thin Solid Films*, Dover, Chapter 4. It should be noted that these equations are valid for both s- and p-polarized light.

In response to incident light **14** substrate **16** and stacks of films **36**, **38** generate response light. The response light includes both reflected light **24** and transmitted light **28**. The response spectrum of reflected light **24** detected by detector **26** is obtained by multiplying complex reflectance amplitude r by its complex conjugate r*. This multiplication yields a reflectance R:

$$R = r \cdot r^*. \qquad \text{Eq. 5}$$

Similarly, the response spectrum of transmitted light **28** detected by detector **30** is described by a transmittance T. Transmittance T is obtained by multiplying complex transmittance amplitude t by its complex conjugate t* as follows:

$$T = t \cdot t^*. \qquad \text{Eq. 6}$$

The choice of range $\Delta\lambda$ of incident light **14** is such that substrate **16** is semi-transparent or event transparent at any particular wavelength, e.g., at λ_i, within range $\Delta\lambda$. Therefore, at a particular wavelength, e.g., at λ_i, response light **24, 28** undergoes multiple internal reflections and transmissions before emerging from substrate **16**.

Depending on a vertical coherence length L_{vc} of light **14** response light **24, 28** is coherent or incoherent. More precisely, when vertical coherence length L_{vc} is sufficiently small with respect to thickness d_s of substrate **16** then response light **24, 28** exhibits incoherence. This is visualized in Fig. 1 for response light **24, 28** at wavelength λ_i by showing a "slip-off" in phase δ_s produced after several internal reflections. For a source **12** with 2 nm line width (which gives vertical coherence length $L_{vc} \sim 0.1$ mm at 500 nm) and thickness d_s larger than 0.2 mm response light **24, 28** undergoes multiple reflections within substrate **16** and exhibits incoherence.

When response light **24, 28** exhibits incoherence then phase δ_s of the complex-valued responses, i.e., complex reflectance and transmission amplitudes r, t needs to be averaged. Averaging of phase δ_s yields the following reflectance R and transmittance T:

$$R = \frac{1}{2\pi}\int_0^{2\pi} r \cdot r^* \, d\delta_s \text{, or}$$

$$= \frac{r_{as}r_{as}^* + \left(t_{as}t_{as}^*t_{sa}t_{sa}^* - r_{as}r_{as}^*r_{sa}r_{sa}^*\right)r_{sb}r_{sb}^*e^{-2\alpha_s d_s}}{1 - r_{sa}r_{sa}^*r_{sb}r_{sb}^*e^{-2\alpha_s d_s}}, \quad \text{Eq. 7}$$

$$T = \frac{1}{2\pi}\int_0^{2\pi} t \cdot t^* \, d\delta_s \text{, or}$$

$$= \frac{t_{as}t_{as}^*t_{sb}t_{sb}^*e^{-\alpha_s d_s}}{1 - r_{sa}r_{sa}^*r_{sb}r_{sb}^*e^{-2\alpha_s d_s}}. \quad \text{Eq. 8}$$

The response spectra, in this case reflectance R and transmittance T, account for the complex-valued transmittance and reflectance amplitudes r, t due to substrate **16** and stacks **36, 38**.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The method of invention is based on the fact that knowledge of materials making up films **36, 38** and substrate **16,** as well as their physical dimensions yield the information necessary to compute complex-valued reflectance and transmittance amplitudes r, t. Therefore, in practicing the method of invention the complex-valued response due to the features such as films **36, 38** and substrate **16** has to be known before measurement. The computed complex-valued response is used in determining one or

more physical parameters of one or more of films **36, 38** actually being examined on substrate **16.**

The method of invention finds its preferred application in measuring physical properties of features that are adjacent to each other and are located on a semi-transparent or even transparent substrate. Fig. 2 illustrates an apparatus **50** in accordance with the invention for determining one or more physical parameters of features **52A, 52B, … 52N** on a uniform substrate **54.** Features **52A, 52B, … 52N** are made of two different materials and are positioned adjacent each other. In this embodiment odd numbered features, i.e., **52A, 52C, 52E, …** etc. are made of material 1 such as amorphous fused silica and even numbered features, i.e., **52B, 52D, 52F, …** etc. are made of material 2 such as air (air gaps). This type of arrangement of features **52** is encountered, for example, in an Alternating Aperture Phase Shift Mask (AAPSM). It should be understood, that the arrangement of features **52** can be periodic or non-periodic and that features **52** can be made of more than two types of materials.

In addition to adjacent features **52,** substrate **54** also carries a number of features in the form of layers **53A, 53B** and **53C.** Layers **53** can be made of materials different from those of features **52.**

Apparatus **50** has an illumination source **56.** Illumination source **56** generates an incident light **58** spanning an incident wavelength range $\Delta\lambda$. Preferably source **56** is broadband and its

range $\Delta\lambda$ extends from about 190 nm to about 1000 nm. To cover such range source **56** can include a number of individual sources spanning separate or even overlapping portions of wavelength range $\Delta\lambda$. Substrate **54** is at least semi-transparent within wavelength range $\Delta\lambda$. Of course, the actual level of transparency of substrate **54** to incident light **58** may differ greatly between different wavelengths within range $\Delta\lambda$.

Apparatus **50** is equipped with an optic **60** for guiding incident light **58** from source **56** to substrate **54.** Optic **60** is shown in the form of a lens, but it is understood that a compound optic system can be used as optic **60.** In particular, it is preferred that optic **60** have a beam shaping power such that it can focus or collimate incident light **58** on substrate **54,** as indicated in dashed and dotted lines.

An optic **62** is positioned above substrate **54** to guide response light **64** generated in response to incident light **58** by substrate **54** and features **52, 53** to a detector **66.** Although optic **62** is shown in the form of a lens, it is understood that a compound optic system can be used as optic **62.** Response light **64** is a reflected light and it has a response spectrum corresponding to a reflectance R of substrate **54** and features **52, 53.** An additional optic **68** and detector **70** can be provided to also collect a response light **72** transmitted through features **52, 53** and substrate **54.** Response light **72** has a response spectrum corresponding to a transmittance T of features **52, 53** and substrate **54.**

Apparatus **50** has a detector **66** for receiving response light **64** and a detector **70** for receiving response light **72.** Detectors **66, 70** are any suitable photodetectors for receiving response light **64, 72** respectively and measuring a response spectrum of response light **64, 72.** More specifically, detectors **66, 70** are designed to measure response light **64, 72** over a response spectrum covering entire wavelength range $\Delta\lambda$.

Furthermore, each detector **64, 70** is connected to a processing unit **74, 76** respectively. Processing units **74, 76** analyze the response spectra and perform computations to obtain computed reflectance and transmittance amplitudes r, t or else import reflectance and transmittance amplitudes r, t from elsewhere. In the embodiment shown units **74, 76** can be in communication with each other, as indicated by the dashed line. It should be noted that in alternative embodiments units **74, 76** can be combined in a single processing device or unit.

During determination of one or more physical parameters of features **52, 53** detectors **66, 70** receive response light **64, 72** from substrate **54** and features **52, 53.** Detectors **66, 70** measure the response spectrum of response light **64, 72.** In this case detector **66** measures reflectance R and detector **70** measures transmittance T over wavelength range $\Delta\lambda$. Deviations of reflectance R and transmittance T measured by detectors **66, 70** from the values computed using the complex-valued reflectance and transmittance amplitudes r, t are used by processing units **74, 76** to determine the one or more physical parameters of one or more of features **52, 53.** The physical parameter or

parameters can include a depth or thickness, a width, a real part of the complex refractive index, an imaginary part of the complex refractive index or some other physical parameter of any one of features **52, 53**.

Processing units **74, 76** determine the one or more physical properties of features **52, 53** based on a computed complex-valued response for a sample of desired dimensions and material composition and measured response spectrum or spectra, such as the reflectance R and/or transmittance T. In some embodiments the complex-valued response can be computed with the aid of measurements of a suitable reference sample that is built of substrate **54** with features **52, 53** just like the samples to be tested. Alternatively, the complex-valued response can be derived purely mathematically.

During operation, optic **60** guides incident light **58** such that it is incident on an area composing a number of features **52**, specifically features **52A** through **52N**. Since in the present embodiment features **52** may form a periodic structure the area illuminated by incident light **58** should be kept small to avoid possible diffraction effects. Preferably, the area illuminated by incident light **58** should cover a sufficiently small number of features **52** such that diffraction effects are negligible. For example, when working in wavelength range $\Delta\lambda$ from 190 nm to 1000 nm with features **52** on the order of tens to hundreds of nanometers, the number of features **52** illuminated by incident light **58** should be kept under 50 and even under 20 in some cases. This condition is not as crucial or may even be

unnecessary when features **52** are not arranged in a periodic structure. To take into account the diffraction effects the complex response has to be computed using vector theory. Additional information and relevant teaching on the application of the vector theory can be found in U.S. Pat. Nos. 6,483,580; 5,963,329; 5,739,909 and 5,607,800.

Incident light **58** has a lateral coherence length L_{lc} as indicated. It should be noted that, in general, lateral coherence length L_{lc} is not equal and may differ quite substantially from vertical coherence length L_{vc}. When the size of adjacent features **52** is smaller than coherence length L_{lc} the response light **64, 72** from adjacent features **52** is added coherently. Thus, when the area fractions covered by features **52** made of material 1 (i.e., features **52A, 52C,** …) and made of material 2 (i.e., features **52B, 52D,** …) correspond to a_1 and a_2, respectively, then the total complex-valued reflectance and transmittance amplitudes are given by the combination of amplitudes of response light **64, 72** from these two areas, as follows:

$$r_C = a_1 r_1 + a_2 r_2, \qquad \text{Eq. 9}$$

$$t_C = a_1 t_1 + a_2 t_2, \qquad \text{Eq. 10}$$

$$a_1 + a_2 = 1, \qquad \text{Eq. 11}$$

where the subscript "C" denotes coherent adding. It should be noted that r_1, r_2, t_1, t_2 are the complex-valued reflectance and transmittance amplitudes for areas 1 and 2, respectively, and they may be calculated in accordance with equations 1-2 as

discussed above. The response spectra such as a coherent reflectance R_C and a coherent transmittance T_C are computed by multiplying out the complex-valued reflectance and the complex-valued transmittance by their respective complex conjugates as follows:

$$\begin{aligned} R_C &= (a_1 r_1 + a_2 r_2)\cdot(a_1 r_1 + a_2 r_2)^* \\ &= a_1^2 R_1 + a_2^2 R_2 + 2a_1 a_2 \cdot Real\left(r_1 \cdot r_2^*\right) \end{aligned} \qquad \text{Eq. 12}$$

$$\begin{aligned} T_C &= (a_1 t_1 + a_2 t_2)\cdot(a_1 t_1 + a_2 t_2)^* \\ &= a_1^2 T_1 + a_2^2 T_2 + 2a_1 a_2 \cdot Real\left(t_1 \cdot t_2^*\right) \end{aligned} \qquad \text{Eq. 13}$$

where $R_1=(r_1 \bullet r_1^*)$, $R_2=(r_2 \bullet r_2^*)$, $T_1=(t_1 \bullet t_1^*)$, and $T_2=(t_2 \bullet t_2^*)$ are reflectances and transmittances from areas 1 and 2 respectively.

As discussed above, when substrate **54** is thick, phase δ_s has to be averaged. R_1, R_2, T_1, and T_2 can then be calculated from equations 7 and 8. The cross terms are given by:

$$r_1 \cdot r_2^* \Rightarrow \left\langle r_1 \cdot r_2^* \right\rangle = \frac{1}{2\pi}\int_0^{2\pi} r_1 \cdot r_2^* d\delta_s$$

$$= \frac{r_{1,as} r_{2,as}^* + \left(t_{1,as} t_{2,as}^* t_{1,sa} t_{2,sa}^* - r_{1,as} r_{2,as}^* r_{2,sa} r_{2,sa}^*\right) r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}}{1 - r_{1,sa} r_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}} \qquad \text{Eq. 14}$$

$$t_1 \cdot t_2^* \Rightarrow \left\langle t_1 \cdot t_2^* \right\rangle$$

$$= \frac{1}{2\pi}\int_0^{2\pi} t_1 \cdot t_2^* d\delta_s = \frac{t_{1,as}t_{2,as}^* t_{1,sb} t_{2,sb}^* e^{-\alpha_s d_s}}{1 - r_{1,sa} r_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}} = Ae^{i\phi} \qquad \text{Eq. 15}$$

In these equations subscripts 1 and 2 represent areas 1 and 2, respectively. A is the amplitude of $\langle t_1 \bullet t_2^* \rangle$ and ϕ is the phase difference or shift between t_1 and t_2. A person skilled in the art will recognize that equation 15 provides a very convenient way for measuring and calculating the phase shift for phase masks such as AAPSMs. Equations 12-15 are novel in providing an analytic and closed form expression for coherent lateral interference between adjacent features on thick transparent or semi-transparent substrates. It should be noted that knowledge of phase shift ϕ will be sufficient in some cases to make some determination about physical parameters of features **52**, and is a valuable piece of information in and of itself, as will be appreciated by those skilled in the art.

Light **24, 28** have response spectra which are influenced by complex reflectance and transmittance amplitudes r_C and t_C. Specifically, the presence of the cross terms $\langle r_1 \bullet r_2^* \rangle$ and $\langle t_1 \bullet t_2^* \rangle$ in equations 12 and 13 affects the response spectra such as the reflectance R and transmittance T over wavelength range $\Delta\lambda$. In fact, because of the cross terms the total reflectance R and total transmittance T within range $\Delta\lambda$ experience interference effects such their sum may be less than 1 (assuming no absorption losses).

Equations 14-15 can be simplified in some cases. For example, when substrate **54** is thick and highly absorbing such that:

$$\alpha_s d_s >> 1 \ or \ e^{-\alpha_s d_s} \approx 0,$$

then the expressions for the cross terms can be simplified as follows:

$$\langle r_1 \cdot r_2^* \rangle = r_{1,as} r_{2,as}^*, \text{ and} \qquad \text{Eq. 16}$$

$$\langle t_1 \cdot t_2^* \rangle = 0. \qquad \text{Eq. 17}$$

For measurement purposes, it is sometimes convenient for optic **60** to produce a focused beam of incident light **58** rather than a collimated beam. One extreme case is when the depth of field is much shorter than thickness d_s of substrate **54**. If the beam of light **58** is focused on one side of substrate **54**, e.g., on side a, then the reflectance from the other side, i.e., side b of substrate **54** will not be detected. Therefore, when the beam of light **58** is focused on side a, which is the front side or front surface, equation 14 will be changed to equation 16 by setting $r_{i,sb}=0$. On the other hand, when the beam of light **58** is focused on side b, which is the back side or back surface, equation 14 will be changed ($r_{i,sa}=0$, $r_{i,as}=0$) to:

$$\langle r_1 \cdot r_2^* \rangle = t_{1,as} t_{2,as}^* t_{1,sa} t_{2,sa}^* r_{1,sb} r_{2,sb}^* e^{-2\alpha_s d_s}. \qquad \text{Eq. 18}$$

R_1 and R_2 in equation 12 need to be modified accordingly.

When the size of area 1 and 2 is much larger than lateral coherence length L_{1c} of incident light **58,** then response light **64,** **72** from those two areas add incoherently. Thus, the total reflectance and transmittance are given by:

$$R_I = a_1 R_1 + a_2 R_2, \qquad \text{Eq. 19}$$

$$T_I = a_1 T_1 + a_2 T_2, \qquad \text{Eq. 20}$$

where the subscript "I" denotes incoherent adding. It should be noted that equations 9-10 and 19-20 can be extended to cases where three, four or even more different areas are illuminated.

In most practical embodiments, response light **64,** **72** from area 1 and area 2 are partially coherent. Thus, the reflectance R and transmittance T including the contributions of both coherent and incoherent fractions to their response spectra can be described as follows:

$$R = (1-\beta) R_I + \beta R_C, \qquad \text{Eq. 21}$$

$$T = (1-\beta) T_I + \beta T_C, \text{ and} \qquad \text{Eq. 22}$$

$$0 \le \beta \le 1 \qquad \text{Eq. 23}$$

where β is a fraction for coherent adding. Now, when material 1 and material 2 are identical through the whole stack (i.e., substrate **54** and features **52,** **53**) then $R=R_I=R_C=R_1=R_2$ and $T=T_I=T_C=T_1=T_2$ independent of b, a_1 and a_2.

Fraction β, also called the coherence fraction, is related to lateral coherence length L_{lc} as follows:

$$L_{lc} = \frac{\lambda^2}{\Delta\lambda_{spect.}} \qquad \text{Eq. 24}$$

where λ is the wavelength and $\Delta\lambda_{spect.}$ is the spectral band width of detectors **66, 70** and preferably covers the entire bandwidth $\Delta\lambda$ of incident light **58**. For more information the reader is referred to Grant R. Fowles, *Introduction to Modern Optics*, Second Edition, Dover, 1975, p. 73. Usually, the first order of diffracted response light is used and the grating equation is given by:

$$\lambda = p(\sin\theta_i + \sin\theta_r) \qquad \text{Eq. 25}$$

where p is the period of the grating, and θ_i, θ_r are the angles for incident and diffracted light. This equation can be re-written as:

$$\Delta\lambda = \sqrt{p^2 - (\lambda - p\sin\theta_i)^2}\,\Delta\theta_r, \qquad \text{Eq. 26}$$

where $\Delta\theta_r$ is the angular spread of the diffracted response light. Using equation 26 coherent fraction β can be approximated by:

$$\beta = \frac{\beta_1\lambda^2}{\beta_0\sqrt{p^2 - (\lambda - p\sin\theta_i)^2}}$$ when $\beta < 1$, and

$\beta=1$ otherwise. Eq. 27

In equation 27 β_1 is the coherent factor (wavelength independent) and β_o is the normalization factor given by:

$$\beta_0 = \frac{\lambda_o^2}{\sqrt{p^2 - (\lambda_o - p\sin\theta_i)^2}}, \qquad \text{Eq. 28}$$

where λ_o is the shortest wavelength in the collected spectrum $\Delta\lambda_i$.

The above equations are used to determine the response spectra, i.e., reflectance R and transmittance T that should be observed by detectors **66, 70** when the sample being measured conforms to the requirements. In practice, processing unit **74** compares these computed or theoretical spectra with actual measured spectra obtained from detectors **66, 70.**

It should be noted at this point, that all of the above approaches can be applied to unpolarized light, s-polarized light and p-polarized light. A person skilled in the art will also recognize that the method of invention permits one to perform computations and measurements for a wide variety of feature geometries and materials on semi-transparent and transparent substrates. The below selected examples serve to

further illustrate how the method and apparatus of invention are applied for performing measurements on specific samples.

EXAMPLES

Fig. 3 illustrates a fused silica sample **99** having adjacent features **100, 102** on a substrate **104.** Sample **99** is examined with the aid of apparatus **50** shown in Fig. 2. A beam **106** of incident light **58** spanning wavelength range $\Delta\lambda$ and originating from source **56** is shown. The remainder of apparatus **50** and response light are not shown in Fig. 3 for reasons of clarity.

Substrate **104** is made of fused silica and features **100** are mesas of fused silica. Features **102** are trenches or air gaps between mesas **100.** Trenches **102** can be etched or produced in accordance with any suitable method known in the art.

In sample **99** material 1 is fused silica and material 2 is air. The area fractions a_1 and a_2 of mesas **100** and trenches **102** are equal and the depth t_s of trenches **102** is 240.9 nm. The calculated response spectrum of response light (reflected and transmitted light) includes both the reflectance and transmittance spectra R, T obtained by using equations 12 and 13 and plotted in Fig. 4. Reflectance R from front (etched) side **a** (solid line) and back side **b** (dashed line) of sample **99** are referenced by **108** and **110** respectively. Transmittance is drawn in solid line indicated by reference number **112.** Reflectance **110** from back side **b** exhibits more oscillations (peaks and valleys). This is because fused silica has a higher refractive index than air. This makes it advantageous to measure

reflectance R from the back side **b** of etched sample **99**. This is especially useful when Cr is coated on sample **99,** such as when producing an AAPSM mask.

The phase ϕ is calculated using equation 15, and the results are shown by graph **114** in Fig. 5. The phase shift is 180.0 degrees at a wavelength λ=248 nm. The destructive interference results in zero intensity in transmittance spectrum **112** at 248 nm as can be seen in Fig. 4, since the area fractions a_1 and a_2 are 50%.

The wavelength for the 180 degree phase shift can be directly measured using transmittance spectrum **112,** as more clearly shown in Fig. 6. In fact, the solid lines are the raw transmittance spectra **112A, 112B, 112C, 112D** and **112E** for five different area fractions a_2 *(0%, 5%, 10%, 20% and 40%) of trenches* **102** *in* samples analogous to sample **99.** The positions of the dips are at 248 nm for higher area fractions a_2 and slightly off for lower area fractions a_2. The dashed lines are the transmittances normalized by the 0% raw transmittance spectrum **112** to remove the wavelength dependence of the substrate **104** spectrum.

With the aid of normalization the dip position is fixed at 248 nm, independent of fractional area a_2 covered by trenches **102.** This allows one to measure the physical parameter of depth t_s of trenches **102** and phase shift ϕ_T at any wavelength λ through normalized transmittance (by dividing T_1 (=T_2) on both sides of equation 13):

$$T_n = a_1^2 + a_2^2 + 2a_1 a_2 \cos\phi_T, \qquad \text{Eq. 29}$$

$$\phi_T = \frac{2\pi(n\cos\theta_2 - \cos\theta_1)t_s}{\lambda}, \qquad \text{Eq. 30}$$

where n is the refractive index of fused silica, θ_1 is the incident angle and angle θ_2 is given by Snell's law ($n\sin\theta_2=\sin\theta_1$ assuming sample **99** is surrounded by air with $n_{air}=1$) and subscript T on phase ϕ indicates that the response light is transmitted. In Fig. 6, $\theta_1=\theta_2=0$, and $\phi_T=180°$ at $\lambda=248$ nm. Using n=1.5148 at 248 nm, in the measurement the measured physical parameter of trench depth of trenches **102** is $t_s=240.9$ nm. This result is in excellent agreement with the actual trench depth (240.9 nm) and illustrates the efficacy and accuracy of the method of invention. Once the trench depth is obtained, the phase shift ϕ_T at any wavelength λ within range $\Delta\lambda$ can be calculated by using equation 30 and the corresponding value of refractive index n. It should be noted that T_n may have multiple minima when t_s is large.

Similarly, one can obtain the normalized reflectance spectrum R_1 on both sides of equation 12:

$$R_n = a_1^2 + a_2^2 + 2a_1a_2\cos\phi_R. \qquad \text{Eq. 31}$$

When incident light **58** is illuminated from the back side (side **b**), ϕ_R is simply given by:

$$\phi_R = \frac{4\pi n t_s \cos\theta_2}{\lambda}, \qquad \text{Eq. 32}$$

where the subscript R on phase ϕ indicates that the response light is reflected.

An example is shown in the graph of Fig. 7 for samples analogous to sample **99** as described above for the same area fractions a_2 as studied in Fig. 6 (namely 0%, 5%, 10%, 20% and 40%). The peak and valley positions in the normalized reflectance spectra R_n **110A, 110B, 110C, 110D** and **110E** taken from back side **b** remain constant for corresponding area fractions a_2 of 0%, 5%, 10%, 20% and 40%. The extremes (peaks and valleys) are found at $\phi_R = m\pi$, where m is the interference order and is an even number for peaks and an odd number for valleys. Using equations 31 and 32, one can fit R_n by varying t_s and area fraction a_2 with constraints from equation 11. Once t_s is obtained, one can calculate the phase shift for any wavelength λ using equation 32. One can also obtain t_s from two data points in the reflectance spectrum R_n. For example, one can select two extremes (at λ_1 and at λ_2), and calculate t_s as follows:

$$t_s = \frac{\Delta m \lambda_1 \lambda_2}{4|n_1\lambda_2 - n_2\lambda_1|\cos\theta_2}, \qquad \text{Eq. 33}$$

where n_1 and n_2 are the refractive indices of substrate **104** at wavelengths λ_1 and λ_2, respectively, and Δm is the order difference of the interferences. In Fig. 7 one can choose λ_1=212

nm (valley) and λ_2=699 nm (peak), with n_1=1.539, n_2=1.450, Δm=5, and θ_2=0. With these parameters equation 33 yields the physical parameter of trench depth of t_s=241.0 nm, which is very close to the true value of 240.9 nm. Once again, this attests to the efficacy and accuracy of the method and apparatus of the invention.

When beam **106** of incident light **58** is focused and light **58** is incident from side **a**, ϕ_R for thick substrate **104** is given by:

$$\phi_R = \frac{4\pi n t_s \cos\theta_2}{\lambda}. \qquad \text{Eq. 34}$$

In this case phase ϕ_R is independent of the refractive index. Hence, one can fit equations 31 and 34 by simply adjusting a_1^2, a_2^2 and t_s. One can also use equation 33 to calculate t_s, with n_1=n_2=1.0. Graphs of normalized reflectances for incident light **58** being illuminated from side **a** and area fractions a_2 ranging from 0% to 40% as above are shown in Fig. 8. Note that incident light **58** is focused on front side **a** in this case.

Fig. 9 shows a portion of another sample **120** having a substrate **122** of fused silica with trenches **124** (only one shown in Fig. 9). In sample **120** substrate **122** has three films **126A**, **126B** and **126C** on side **a**. Features **128** are mesas between trenches **124** passing down through all three films **126A**, **126B** and **126C**. The depth of trenches **124** can be measured from front side **a** or from back side **b** using equations 21 and 22. In general, the measurement from back side **b** is more sensitive to substrate **122**

recess. This is particularly true for samples in which there is a metal film. For example, a sample **130** with a layer **132** of Cr on side **a** of a fused silica substrate **134** as shown in Fig. 10 is best examined from back side **b**.

Fig. 11 illustrates the graphs for reflectance measurements on sample **130** from front side **a** and from back side **b**. The thickness of layer **132** of Cr and recess in fused silica were held constant at a total value of 300.9 nm. The recess itself was tested at two values: 240.9 nm (solid line) and 230.9 nm (dashed line), respectively. The measurement from front side **a** shows no sensitivity to the change of recess whereas the measurement from back side **b** shows great sensitivity.

ALTERNATIVE EMBODIMENTS

The present method and apparatus are superior to prior art solutions, such as the standard transmission-type interferometric apparatus **140** shown in Fig. 12 for comparison purposes. Specifically, apparatus **140** is not convenient for examining a substrate **142** with features that include mesas **144** and air gaps **146**. In this case mesas have three layers including at the bottom a layer of the substrate material, on top of which are located layers **148** and **150**. An interferometer **152** is positioned to receive two beams **154, 156** passing through two adjacent features **144, 146**.

The limitations of interferometric apparatus **140** are, among other, the fact that beams **154, 156** have to be transmitted through substrate **140** and features **144, 146** in order to enable

measurement of physical parameters of features **144, 146.** When one of layers **148, 150** or substrate **142** are not transparent, then apparatus **140** will not be able to perform the measurement.

In contrast, an apparatus according to the present invention offers a number of options for measuring one or more physical parameters of features **144, 146** on substrate **142** irrespective of the transmissibility of layers **148, 150.** As shown in Fig. 13 this can be performed in the reflective mode using a beam of incident light **160** and a reflected response light **162.** Alternatively, a beam of incident light **164** illuminates substrate **142** from the back side to produce a reflected response light **166**, as shown in Fig. 14. As noted in the examples above, under certain circumstances measurement using reflected response light **166** from the back side will provide higher accuracy measurements than light **162** reflected from the front side. In still another embodiment, a beam of incident light **168** is directed at substrate **142** and a transmitted response light **170** is measured. As will be appreciated by a person skilled in the art, a combination of all three methods illustrated in Figs. 13-15 can be used depending on the transmission and reflection properties of substrate **142** and features **144, 146.**

Fig. 16 illustrates a portion of yet another apparatus **180** for examining physical parameters of features **182, 184** of a sample **186.** In this embodiment features **182** are embedded within feature **184.** Feature **184** is a flat film deposited on a semi-transparent substrate **188.** Apparatus **180** has a source **190** for producing a beam of incident light **192** for illuminating sample

186. Apparatus **180** has a detector **194** for examining a response light **196** reflected by sample **186.** It should be noted that a transmitted response light **198** can also be measured as necessary. Transmitted response light **198** can be measured by detector **194** with the aid of additional optics (not shown) or a separate detector and optics (not shown).

Apparatus **180** takes advantage of the fact that refractive, catadioptric or purely reflective optics can be used to guide incident light **192** and response light **196** (**198**). In fact, purely reflective optics are advantageous when incident wavelength range $\Delta\lambda$ is large, e.g., when it extends from 190 nm to 1000 nm. In the present embodiment $\Delta\lambda$ is large and thus apparatus **180** employs a set of reflective optics **200, 202** in the form of curved mirrors. Mirror **200** directs incident light **192** to sample **186.** Mirror **202** receives response light **196** from sample **186** and directs it to detector **194.** In a preferred version of apparatus **180** mirrors **200, 202** are torroidal mirrors. For general information about the use of torroidal mirrors the reader is referred to U.S. Pat. No. 5,991,022.

In view of the above, it will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.